

Effect of solar wind density on relativistic electrons at geosynchronous orbit

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[1] We examined the relationship between relativistic (>2 MeV) electron fluxes at geostationary orbit and two solar wind parameters, the speed and density. For the analysis, we used data of relativistic electron fluxes measured with GOES-8 spacecraft for 1997–2002 and GOES-10 spacecraft for 2003–2006, and solar wind data, provided by Goddard Space Flight Center. Using the correlation analysis, we found that not only solar wind speed but also solar wind density provides a strong effect on relativistic electrons: the relativistic electron fluxes increase with increasing solar wind speed and decrease with increasing solar wind density. In contrast to solar wind speed that shows the best correlation with electron fluxes after about two days only, the solar wind density shows the best correlation with the electron fluxes after about 15 hours. To separate the effects of solar wind speed and density, we examined events when solar wind speed varied insignificantly; in these events, the effect of solar wind density on the relativistic electrons remained strong. We found that the solar wind density, which may affect the loss of relativistic electrons, effectively controls the magnitude of relativistic electron fluxes at geostationary orbit, so that the strongest fluxes occurred almost exclusively during low-density solar wind conditions. Thus, our study showed that solar wind density is an important parameter that may significantly affect the loss of relativistic electrons and, as a result, the resulting magnitude of the electron fluxes at geostationary orbit.

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1. Introduction

[2] Enhanced fluxes of relativistic electrons appear in the Earth's magnetosphere following some magnetic storms. These electrons can cause a serious damage to satellites and humans in space [e.g., Baker, 2002], and understanding the processes related to their generation are of high importance. However, despite the efforts of many researchers, the cause for the generation and decay of these electrons is not completely clear. It is not clear why only half of geomagnetic storms are followed by enhanced relativistic electron fluxes [Reeves *et al.*, 2003], and why relativistic electron fluxes well correlate with solar wind speed but much worse correlate with geomagnetic activity indices [Paulikas and Blake, 1979; Baker *et al.*, 1998; Li and Temerin, 2001; Li *et al.*, 2001; O'Brien *et al.*, 2001], and many other questions remain yet unanswered.

[3] Most researchers [e.g., Baker *et al.*, 1998; Li and Temerin, 2001; Li *et al.*, 2005; Summers *et al.*, 2007] agree that the generation of relativistic electrons may include two stages: a primarily acceleration of electrons to ~ 100 keV by electric fields associated with substorm activity in nightside magnetosphere, and secondary acceleration by either ULF or VLF whistler-mode waves. The adiabatic acceleration by ULF waves, associated with the radial drift of accelerated electrons toward the Earth, was discussed by Rostoker *et al.* [1998], Elkington *et al.* [1999], Hudson *et al.* [1999], Li and Temerin [2001], and Li *et al.* [2001, 2005]. The local non-adiabatic acceleration, associated with wave-particle interaction near the electron gyroresonance, was discussed by Horne *et al.* [2005], Thorne *et al.* [2005], Summers *et al.* [2007], and many others. Recent theoretical and experimental studies showed that whistler-mode chorus emissions, having large amplitudes and associated commonly with auroral substorms, may be a main factor responsible for acceleration of ~ 100 -keV electrons, generated during auroral substorms (so-called “seed” population), to relativistic energies [Meredith *et al.*, 2003; Thorne *et al.*, 2005; Summers *et al.*, 2007]. The results of statistical studies, however, showed [Paulikas and Blake, 1979; Baker *et al.*, 1998; Li and Temerin, 2001; Li *et al.*, 2005] that electron fluxes were most well correlated with solar wind speed, while the correlation with other parameters of solar wind plasma was significantly weaker. The cause for this is not clear, and this result remains puzzling if not a “mystery” [e.g., Li and Temerin, 2001] though in the following paper by Li *et al.* [2001], these authors purported to solve this ‘mystery’ at least to some extent.

[4] The purpose of this paper is to investigate the effect of solar wind density on the loss and magnitude of relativistic electron fluxes at geostationary orbit.

2. Data Used for Analysis

[5] We used the 3-hour mean data of relativistic (>2 MeV) electron fluxes measured with two geostationary satellites: the GOES-8 spacecraft for six years from 1997 through 2002, and the GOES-10 spacecraft for four years from 2003 through 2006. The data are available from the NOAA web side at <http://spidr.ngdc.noaa.gov>. We also used solar wind data available from website of the Goddard Space Flight Center at ftp://nssdcftp.gsfc.nasa.gov/spacecraft_data/omni/, and the *Kp* geomagnetic activity indices available from the NOAA web side at <http://spidr.ngdc.noaa.gov>.

3. Results of Analysis

[6] In this paper, we present the results of correlation analysis between relativistic (>2 MeV) electron fluxes at

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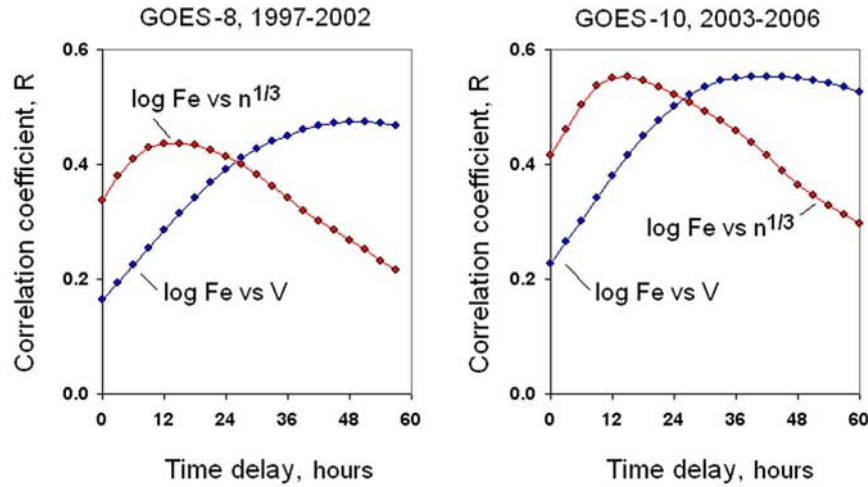


Figure 1. Correlation coefficients for the correlation of $\log F_e$ (where F_e is relativistic electron fluxes in counts/cm²·s·sr) with solar wind speed (V , km/s) and the cube root of solar wind density (n , cm⁻³)^{1/3} as functions of time delay between values of $\log F_e$, measured by GOES-8 (1997–2002) and GOES-10 (2003–2006), and V and n values, respectively. All values are 3-hour averages.

geostationary orbit, and data of solar wind speed and density. In this analysis, we used 3-hour mean values of these parameters as well as the data averaged over longer time intervals. We provided the same analysis for two datasets: for 1997–2002, when we used data for relativistic electrons measured with GOES-8 spacecraft, and for 2003–2006, when we used data from GOES-10 spacecraft. We note that these satellites were located at different meridians, and relativistic electron fluxes, measured with GOES-10, usually exceed significantly those measured with GOES-8 spacecraft. The results of this analysis are presented in Figures 1, 2, and 3.

[7] Figure 1 shows the correlation coefficients computed for the correlation of 3-hour mean values of logarithm of electron fluxes ($\log F_e$) with 3-hour mean values of solar wind speed (V) and the cube root of solar wind density (n) as a functions of time delay between values of $\log F_e$, measured with GOES-8 (1997–2002) and GOES-10 (2003–2006), and V and n values. We used in this figure the correlation of relativistic electron fluxes with the cube root of solar wind density that improved significantly the correlation. Time delay in this figure means a time interval between effecting solar wind parameters (speed and density) and following responses in relativistic electron fluxes.

[8] Figure 1 demonstrates that the effects of solar wind density and speed on relativistic electrons are remarkably different. The effect of solar wind density on relativistic electrons is significant within about 1-day interval before related responses in relativistic electrons, while the effect of solar wind speed becomes significant after about two days. The weak correlation between electron fluxes and solar wind speed within 1-day intervals before related responses in relativistic electrons shows that not the solar wind speed but rather the solar wind density is a main factor that most strongly affects the magnitude of electron fluxes during these intervals. We note that relativistic electron fluxes in Figure 1 correlate positively with solar wind speed but negatively (anti-correlate) with solar wind density, and that averaging the electron fluxes and solar wind parameters over wider time intervals, than 3-hours, improves the correlation.

[9] Figure 2 demonstrates the correlation patterns for 15-hour mean values of the electron fluxes, measured with GOES-8 and GOES-10, versus solar wind speed and the cube root of solar wind density, both averaged over 1.5-day intervals. For solar wind density, the averaging 1.5-day intervals were just prior to the related responses in the electron fluxes, while for solar wind speed, the averaging 1.5-day intervals were shifted by 15 hours to earlier time to improve the correlation between solar wind speed and $\log F_e$ in accordance to Figure 1. Nevertheless, the correlation coefficient between $\log F_e$ and the cube root of solar wind density in Figure 2 is close to or even exceed (for the GOES-10 data) that for the correlation between $\log F_e$ and solar wind speed. This again shows a strong effect of solar wind density on relativistic electrons.

[10] Due to the well-known tendency of solar wind speed and density to anti-correlate (high-speed solar wind tends to correspond to low solar wind density, and vice versa), the effects of solar wind speed and density in Figure 2 are partially connected. In order to separate the effects of solar wind speed and density, we selected the events when the solar wind speed within long enough (2-day and more) time intervals before the related variations in electron fluxes was restricted within a narrow range of values. For GOES-8 data, the solar wind speed was restricted within 400–520 km/s; for GOES-10 data it was restricted within 400–550 km/s. For these events, the effect of solar wind speed on relativistic electrons may be neglected (the correlation coefficients for the correlation between $\log F_e$ and solar wind speed for these events did not exceed ~ 0.2). The number of 3-hour electron events after the restriction remained significant: 2177 three-hour events for 1997–2002, and 1982 three-hour events for 2003–2006. Then we calculated the numbers of strong electron events in four ranges of solar wind density.

[11] The results obtained are presented in Figure 3 that shows relative numbers of the 3-hour electron events within each of four solar-wind-density intervals, when $\log F_e$ was higher than 1.5, 2, 2.5, and 3 for GOES-8 data, and higher than 2.5, 3, 3.5, and 4 for GOES-10 data. The intervals for solar wind density were chosen so that

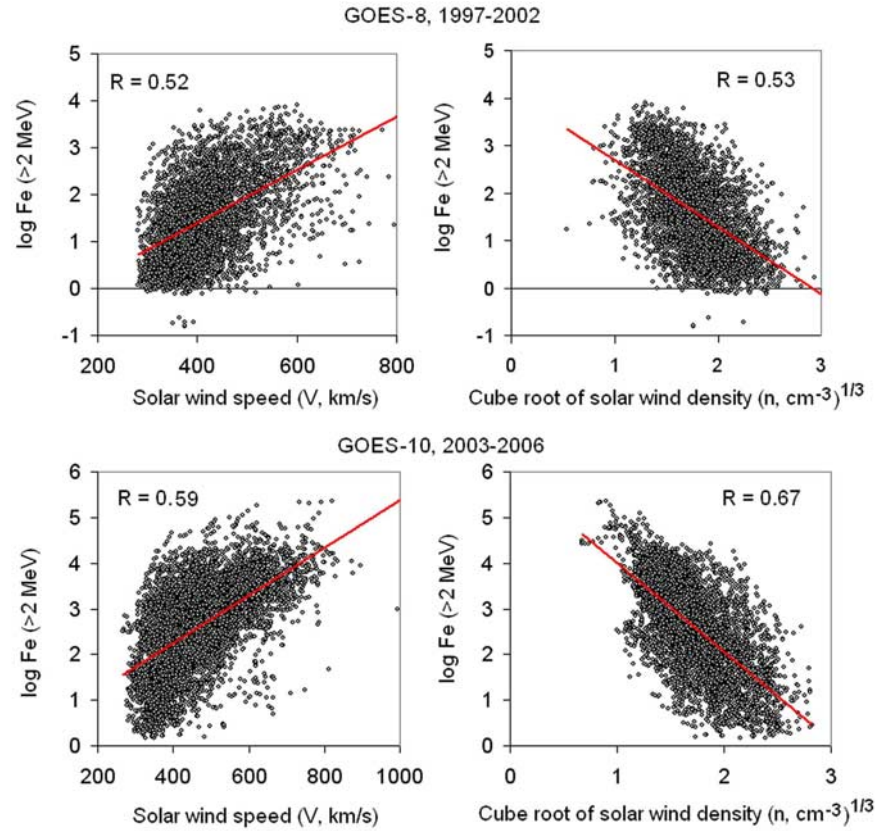


Figure 2. Correlation patterns for 15-hour mean values of $\log F_e$, measured by GOES-8 (1997–2002) and GOES-10 (2003–2006), versus average values of solar wind speed (V , km/s) and the cube root of solar wind density, $(n, \text{cm}^{-3})^{1/3}$. The values of solar wind speed and density were averaged over 1.5 days before the responses in the electron fluxes. The averaging 1.5-day intervals for solar wind speed were shifted by 15 hours towards earlier time, which provided a better correlation with $\log F_e$ (in accordance with Figure 1).

the values of 3-hour mean density, n , within the 2-day intervals before following responses in electron fluxes lie within given ranges of values: between (1–6), (6–12), (12–18), and (18–30) cm^{-3} , respectively.

[12] Figure 3 shows a strong effect of solar wind density on the occurrence of relativistic electrons. The number of electron events with $\log F_e > 2.5$ and 3, measured with the GOES-8, are reduced from about (80–60)% for low-density solar wind ($n_{\text{max}} < 6 \text{ cm}^{-3}$) to about (30–10)% for high-density solar wind. The number of the events with $\log F_e > 1.5$ and 2, measured with GOES-10, are reduced from about (80–60)% for low-density solar wind to about (50–10)% for high-density solar wind. Since solar wind speed in these events was restricted, the variations in the occurrence of relativistic electron fluxes in this figure are caused by the effect of solar wind density. Once more, this clearly shows a very important role played by solar wind density in the formation of relativistic electron fluxes.

4. Discussion and Conclusion

[13] In the present paper, we have found a strong effect of solar wind density on relativistic electrons. In contrast to solar wind speed that shows the best correlation with relativistic electron fluxes after about two days, variations

in solar wind density shows the best correlation with responses in electron fluxes after about 15 hours, and the correlation between $\log F_e$ and solar wind density within the 1-day time interval before the related responses in electron fluxes is much higher than that between $\log F_e$ and solar wind speed. We also found that most powerful fluxes of relativistic electrons occurred almost exclusively during low-density solar wind conditions, while increasing solar wind density caused a significant decrease in the electron fluxes. These results imply that solar wind density is an important parameter that significantly affects the decay of relativistic electrons and, as a result, the magnitude of relativistic electron fluxes at geostationary orbit.

[14] Earlier *Vassiliadis et al.* [2005] from the analysis of the SAMPEX data also found an “intensive” negative pick in the response of the relativistic electron fluxes near geosynchronous orbit after increasing the solar wind density (see *Vassiliadis et al.* [2005, Figure 2b] and the description to this figure). However, this effect is not shown in their Figure 3, which shows their “data-model correlation”. The effect of solar wind density on relativistic electrons, found in this study, is also consistent with recent results by *Onsager et al.* [2007], who reported that “an abrupt increase in the solar wind density may contribute to the radiation belt electron loss”. We separated the competing effects of solar

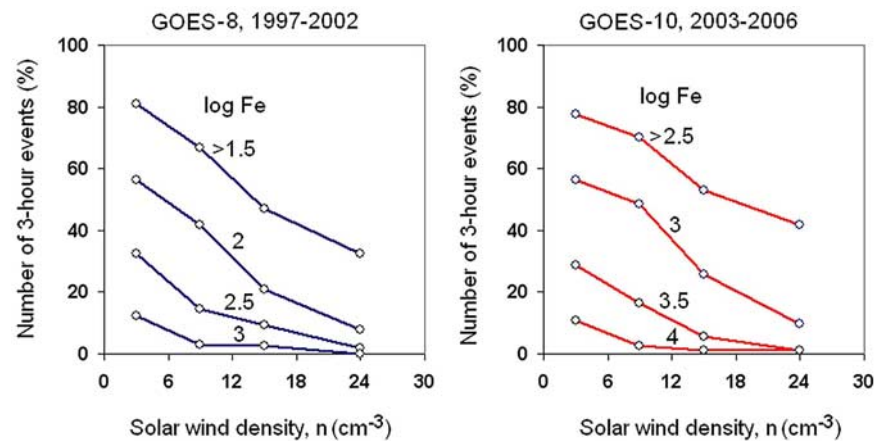


Figure 3. The numbers (in per cent, normalized to each density bin) of 3-hour values of strong relativistic electron events when $\log F_e$ was higher than 1.5, 2, 2.5, and 3 in GOES-8 data (1997–2002), and higher than 2.5, 3, 3.5, and 4 in GOES-10 data (2003–2006). The numbers of such events were calculated for four solar wind density intervals, such that the 3-hour mean densities within 2-day intervals before following responses in electron fluxes lie within given ranges of values: between (1–6), (6–12), (12–18), and (18–30) cm^{-3} , respectively. The numbers of relativistic electron events are attributed to the centers of these intervals, shown with open circles.

wind speed and density on relativistic electrons and found that the strong effect of solar wind density exists independently on solar wind speed, and it effectively controls the total magnitude of relativistic electron fluxes at geostationary orbit, as shown in Figure 3.

[15] The strong effect of solar wind density on relativistic electrons is relatively unexpected because the density is not a primary factor in the generation of geomagnetic disturbances [e.g., Lyatsky and Khazanov, 2007]. Nevertheless, some possible effects of solar wind density on relativistic electrons were discussed in literature. Two main causes responsible for the effect of solar wind density on relativistic electrons may be the compression of dayside magnetosphere by high-density solar wind, and the effect of solar wind density on “shielding” the inner magnetosphere. The first cause, the compression of dayside magnetosphere by high-density solar wind, implies that energetic electrons, while drifting about the Earth along the $B = \text{const}$ contours (that is correct for equatorially-mirroring electrons and approximately correct for other particles) where B is the magnetic field in the magnetosphere equatorial plane, may leave the compressed magnetosphere for the solar wind [e.g., Li *et al.*, 2001; Onsager *et al.*, 2007]. Although this mechanism for electron losses seems reasonable, we found, however, that the correlation of the electron fluxes is not so good with the solar wind pressure; this says that the compression of the magnetosphere is probably not the main factor affecting the loss of relativistic electrons.

[16] Another possible cause for the strong effect of solar wind density on relativistic electrons may be based on the correlation, observed between solar wind density and plasma density in the plasma sheet [Borovsky *et al.*, 1998], which effectively controls “shielding” the inner magnetosphere from penetrating the large-scale electric fields [e.g., Lyatsky *et al.*, 2006, and references therein]. If that is the case, enhanced solar wind density may significantly reduce the penetration of large-scale electric fields into the inner magnetosphere. This results in increasing the

size of the plasmasphere due to filling it with new ionospheric plasma with timescale from few hours to few days [Lawrence *et al.*, 1999], which affects the generation of ion-cyclotron and whistler waves, responsible for losses of energetic electrons [e.g., Meredith *et al.*, 2003; Thorne *et al.*, 2005; Summers *et al.*, 2007]. A similar explanation of the cause for relativistic electron flux dropouts, observed at geostationary orbit, was proposed by Onsager *et al.* [2007]. Both mechanisms, mentioned above, lead to increasing the losses of relativistic electrons from the outer radiation belt. A detailed consideration of these mechanisms is beyond the scope of the present paper.

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